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# Nutrient Dynamics in Cork Harbour

S. Nash<sup>1</sup>, A. Berry<sup>2</sup> & M. Hartnett<sup>1</sup>

<sup>1</sup>*Department of Civil Engineering,*

*National University of Ireland Galway, Ireland.*

<sup>2</sup>*MarCon Computations International Ltd., Ireland.*

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## Abstract

Estuaries are commonly characterised by high productivity due to frequent if not continuous inputs of nutrients from domestic and industrial discharge effluents and from freshwater and marine sources. These forms of nutrient enrichment can lead to eutrophication problems within an estuarine area. Although eutrophication of water bodies is a natural process, it can be greatly accelerated by artificial nutrient enrichment, i.e. nutrient enrichment caused by man's actions. These unnatural increases in a water body's nutrient content can lead to the development of eutrophic conditions with increased plant growth and the occurrence of planktonic algal blooms. However, by using effective management tools, artificial nutrient enrichment may be controlled in such a way as to minimise its environmental impacts on a waterbody.

Cork Harbour is an estuary located on the southwest coast of Ireland. At present a number of industrial and domestic outfalls discharge in the harbour, resulting in nutrient enrichment and increased productivity. One area in particular in the northwest of the harbour, the Lee Estuary / Lough Mahon area, has been classed as eutrophic by the Irish Environmental Protection Agency (EPA). It is proposed to construct a new secondary treatment facility in the Lough Mahon area which will collect a number of existing outfalls, treat their wastes and discharge into Lough Mahon. This paper presents a selection of the findings of a numerical model study carried out to assess the changes, if any, in the trophic status of the Lee Estuary / Lough Mahon area as a result of the proposed treatment facility.

*Keywords:* eutrophication, nutrient enrichment, phytoplankton, water quality model, dissolved oxygen, chlorophyll\_a.

## 1 Introduction

Estuarine waters are commonly characterised by high productivity due to frequent inputs of nutrients from both freshwater and marine sources [1]. These nutrients promote the growth of phytoplankton leading to the potential occurrence of algal blooms. Algal blooms can produce toxins which stress or kill aquatic life, contaminate shellfish and limit the value of the water body for public and recreational use. They can also be unsightly, and can die en-masse causing severe local anoxic conditions with hydrogen sulphide emissions. Petersen *et al* [2] state that toxic blooms in freshwater are correlated with nutrient enrichment and such pollution may also have a role in marine and estuarine toxic algal blooms.

Nutrient enrichment in estuarine waterbodies and ensuing eutrophic conditions may occur either naturally or anthropogenically. The former is not a management problem, the latter, however, is. Anthropogenic nutrient input to an estuary may occur as a result of farming or forestry practices in the form of surface run-off from the surrounding land, or as a result of industrial outfalls or domestic sewage discharges. All of these manmade inputs can be controlled and monitored and by using modern technologies such as numerical prediction models, their environmental impacts can be managed and minimised.

In 2001, the Irish EPA [3] developed a set of Trophic Status Assessment criteria for Irish bays and estuaries which can be used to identify waterbodies in which eutrophication is occurring or may potentially occur with a view to prioritising measures to combat these problems. The criteria, which comprise nutrient enrichment, excessive phytoplankton growth and oxygen disturbance, and are discussed in more detail in Section 3, were used to assess the trophic status of 25 major estuarine and coastal waterbodies, based on water quality data collected over the period 1995-1999 [3] and again for the period 1998-2000 [4]. Within Cork Harbour, a plan view of which is shown in figure 1, Lough Mahon and the Lee Estuary are currently classed as eutrophic and the Owenacurra Estuary / North Channel are classed as potentially eutrophic [1]. These areas are, therefore, highly sensitive to any variations in nutrient input.

The purpose of this research was to aid in the planning and design of a new sewage treatment facility for the city of Cork which is to be located in the northwest of the harbour at Carrigrennan, as shown in figure 1. The new facility will collect and treat a number of the existing outfalls in the vicinity and discharge into Lough Mahon, an area identified by the EPA as being eutrophic. A combined hydrodynamic, solute transport and water quality model was developed for Cork Harbour and used to determine the probable future trophic status of Lough Mahon and the Lee Estuary due to the proposed sewage treatment facility located at Carrigrennan. A number of different sewage discharge scenarios were simulated using the numerical model and the results were analysed using the EPA Trophic Status Assessment criteria. This paper presents the results of some of the numerical model simulations and discusses the findings of the study in relation to the trophic status of Lough Mahon.

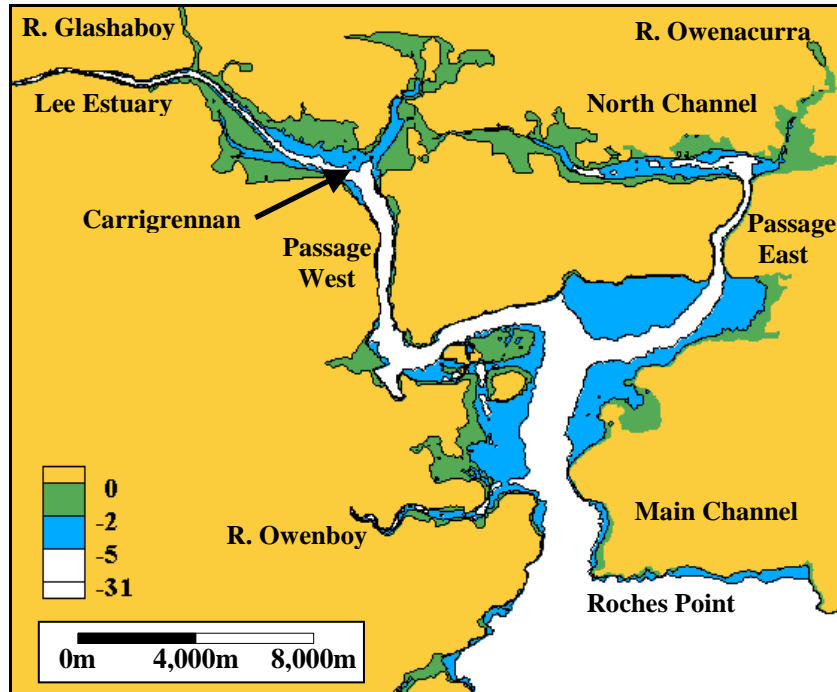


Figure 1: Plan view of Cork Harbour study area (water depths in metres below spring high tide).

## 2 Description of Cork Harbour

Cork Harbour is the deepest, natural harbour in Ireland and one of the largest and most important sea inlets in the country. The estuary's functions are many and varied ranging from a thriving seaport, to a receptacle for domestic and industrial waste, to a popular recreational resource and a vibrant natural resource. In addition, Cork Harbour is also home to the Irish Naval Service.

The extent of the model study area used for this research is shown in figure 1 and covers an area of approximately 354km<sup>2</sup>. As can be seen in the diagram, the study area extends from the lower exits of the River Lee in the northwest to the open sea below Roches Point in the south. The River Lee flows into Lough Mahon which, in turn, enters the main harbour via Passage East and Passage West. The main harbour is connected to the open sea through a deep channel to the south known as the Main Channel.

With the exception of the deeper channels, the water depths in the harbour are quite shallow, as seen in figure 1. The vast proportion of the harbour experiences water depths of less than 5m on a spring tide. In relation to the channels, the maximum water depths are found in the Main Channel where depths of up to

30m exist on a spring tide. The mean tidal range in Cork Harbour is 3.7m on spring tides and 2.0m on neap tides and is fairly typical of inlets on the southern and western coasts of Ireland. As can be seen in figure 2, quite extensive areas of mudflats become exposed within the study area at low water, particularly in the vicinity of Lough Mahon and the North Channel. These areas of mudflats give rise to odours because of decaying organic material deposited there at high water.

The largest provider of freshwater to Cork Harbour is the River Lee which flows through Cork City and empties into Lough Mahon located in the northwest of the estuary. Other substantial freshwater contributors are the Rivers Owenboy, Glashaboy and Owenacurra. However, approximately 74% of the annual volume of freshwater delivered to the estuary by these four rivers can be attributed to the River Lee alone.

Many areas within Cork Harbour are important areas for flora and fauna. A number of sites within the area have been designated as Special Areas of Conservation (SACs), Special Protection Areas (SPAs), Natural Heritage Areas (NHAs) and Wildfowl Sanctuaries while the harbour as a whole has been classed as a Ramsar Site which is a designation assigned to wetlands of international importance. The River Lee is also a designated salmonoid river and as salmon are a migratory fish they must pass through the harbour waters to and from their spawning ground upriver. Therefore, it can be seen that the quality of water in Cork Harbour must be maintained at as high a level as possible and this can only be achieved through effective environmental management.

### **3 Methodology**

#### **3.1 Model Background**

The water quality model used in this study was the Depth Integrated Velocity and Solute Transport model, DIVAST. The model was originally developed by Professor R.A. Falconer at the University of Bradford, UK. It is a 2-D, finite difference model which can be used to simulate time-scales of minutes as well as days and months. The water quality module included in the model is based on the USA EPA formulations included in the QUAL2E model. Readers are referred to Brown and Barnwell [5] for further details.

The model incorporates the following nine water quality parameters and their interactions: salinity, BOD, organic, ammoniacal and nitrate nitrogen, dissolved oxygen, chlorophyll\_a, organic phosphorous and orthophosphate. In most models the population of phytoplankton is estimated by considering the total phytoplankton biomass. In practice the most common method of measuring phytoplankton biomass is to measure a characteristic of all phytoplankton, for example, chlorophyll\_a, and use this as the aggregate variable. This modelling study, therefore, simulates the production of phytoplankton as the production of chlorophyll\_a and the two terms may be substituted for each other throughout this paper.

DIVAST comprises three linked components: a hydrodynamic module a solute transport module and a water quality module. The hydrodynamic module computes water currents and elevations throughout the study area at a 25 second temporal resolution and a 30m spatial resolution. It is based on the solution of the depth integrated Navier-Stokes equations and includes the effects of local and advective accelerations, the rotation of the earth, barotropic and free surface pressure gradients, wind action, bed resistance and a simple mixing length turbulence model. For the water quality and solute transport modules, the general depth integrated advection-diffusion equations are solved, which include local and advective effects, turbulent dispersion and diffusion, wind effects, source and sink inputs and decay and kinetic transformation processes. Thus, the growth, decay and transport of chlorophyll\_a, nutrients and dissolved oxygen are computed based on the hydrodynamics and the interactions between the various water quality parameters.

### **3.2 Model Initialisation**

The hydrodynamic, solute transport and water quality modules of the DIVAST model required a wide range of data to facilitate the accurate modelling of the water quality conditions within Cork Harbour.

The hydrodynamic module required detailed information on the tidal regimes of the areas under consideration. This data included tidal constituents, ranges, periods and times of occurrence for both the spring and neap tidal conditions. The hydrodynamic model was calibrated by ‘tuning’ various parameters, such as, bed roughness, kinematic viscosity and eddy viscosity, until good agreement with a measured hydrodynamic data set was attained. A second data set was then used for validation to ensure that the model was accurately predicting the hydrodynamic regime in the study area.

As with the hydrodynamic module, a number of nutrient and solute concentration values for developing the solute transport and water quality modules were required. These included initial values for all water quality parameters, and flow rates and nutrient loading rates for freshwater inputs, catchment run-off and industrial and domestic discharges. This data was obtained during a detailed sampling programme within the harbour [6]. The solute transport model was calibrated and validated by simulating the salinity fluxes within the harbour and comparing results with measured data. It was also validated against field observations of dye release surveys. To calibrate and validate the water quality module, simulations were carried out modelling the full suite of water quality parameters and comparing predicted chlorophyll\_a concentrations with measured data.

### **3.3 Trophic Assessment**

The predicted trophic status of Cork Harbour was assessed using the Irish EPA’s Trophic Status Assessment System which is presented in detail in McGarrigle *et al* [4]. This system comprises criteria for:

1. enrichment of water by nutrients (as indicated by measurement of dissolved inorganic nitrogen and orthophosphate concentrations)
2. accelerated growth of phytoplankton (as indicated by measurement of chlorophyll\_a concentrations)
3. undesirable disturbance (as indicated by measurement of oxygen status)

The EPA have established threshold values in respect of each of the criteria with reference to the normal values that would typically be observed in waters with low levels of pollution or nutrient enrichment. The Irish Environmental Protection Agency [3] consider that a section of tidal water is eutrophic if the following conditions prevail:

- criteria for MRP or DIN are exceeded *and*
- criteria for chlorophyll\_a are exceeded *and*
- criteria for dissolved oxygen are breached

For the purposes of this study, trophic status was achieved by comparing the predicted levels of dissolved oxygen saturation, chlorophyll\_a, dissolved inorganic nitrogen and orthophosphate with the threshold levels set out by the EPA.

### 3.4 Model Scenarios

Figure 2 shows the locations of the industrial and domestic outfalls in Cork Harbour that are included in all models executed to simulate the existing scenario. A total of twenty outfalls were defined to the numerical models. The numerical models were used to simulate existing conditions in Cork Harbour and predict future conditions as a result of the new treatment facility at Carrigrennan.

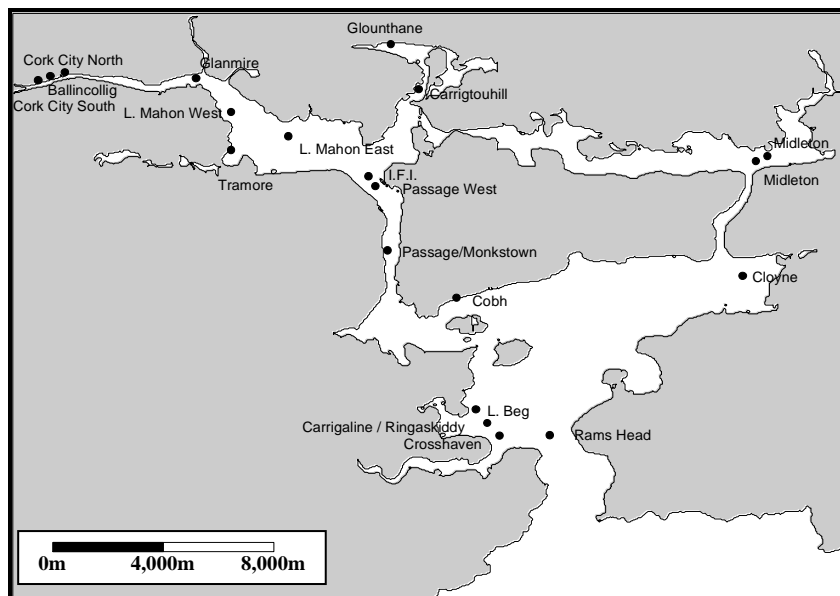


Figure 2: Existing industrial and domestic discharges to Cork Harbour.

The construction of the new treatment facility would mean that the following discharges would be collected together, undergo secondary treatment and then discharge through a single outfall: Cork City North Sewer, Cork City South Sewer, Glounthane, Lough Mahon West, Lough Mahon East, Glanmire and Tramore. The various proposed treatment options as simulated by the model are outlined below:

- **Treatment Option A: Proposed Upgrade to Secondary Treatment**  
The combination of seven discharges into a single discharge and subsequent secondary treatment.
- **Treatment Option B: Nitrogen and Phosphorous Reduction**  
The secondary treated works as in Option A, with additional denitrification to 10mg/litre and phosphorous reduction to 1mg/litre.
- **Treatment Option C: Phosphorous Reduction**  
The secondary treated works as in Option A, with additional phosphorous reduction to 1mg/litre.

Each of the proposed scenarios were executed for typical Summer and Winter conditions with respect to river flows, solute concentrations, temperature and light intensity, resulting in a total of eight simulations including those of the existing conditions.

## 4 Results

Eight model simulations were carried out for the study, each simulating all nine water quality parameters. In order to apply the EPA Trophic Assessment Criteria the predicted concentrations for dissolved oxygen saturation, chlorophyll\_a, dissolved inorganic nitrogen and orthophosphate within the Lough Mahon area, shown in figure 3, were analysed and compared with measured EPA datasets. However, due to the large volume of model results, this paper will only present results for dissolved oxygen (DOX) and chlorophyll\_a (CHL). In addition, the Trophic Assessment system only pertains to summer conditions, therefore, only those results for the summer scenario runs will be discussed.

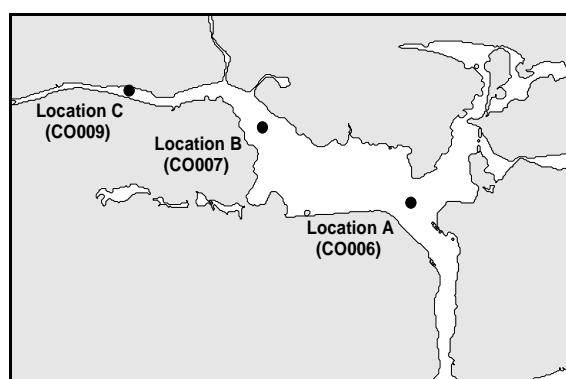


Figure 3: Extent of the Lee Estuary / Lough Mahon water body considered in this study with locations at which model results are presented.



The summer simulations were carried out for expected typical summer conditions with respect to river flows, solute concentrations, temperature, and light intensity. Each simulation was started on June 1st and continued until at least June 25th. The results for each simulation were output as a number of time series analyses at specific points in the Lee Estuary and Lough Mahon study area, the locations of which are shown in figure 3. The model output locations are denoted as Locations A, B and C. The designation in brackets represents the naming convention adopted by the EPA for water quality sampling points sited at or near these locations.

#### 4.1 Simulation Results

The details of treatment options A, B and C have been set out earlier in Section 3.4. The time series of DOX and CHL concentrations as predicted by the model at Location C for each of the treatment options are presented in figure 4 and figure 5 below. The existing summer simulation results are also included in the same plots for comparison.

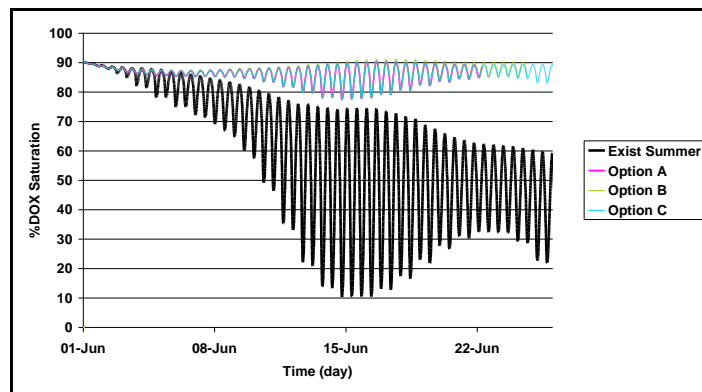


Figure 4: %DOX saturation at Location C (Options A, B & C coincident)

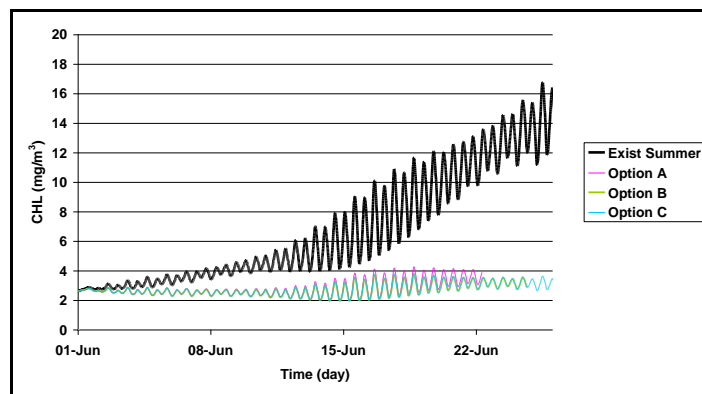


Figure 5: CHL concentrations at Location C (Options B & C coincident)

It can be seen from the graphs above, that all of the three proposed treatment options provide much improved water quality at Location C than that which currently exists. Where DOX saturation levels as low as 10% were experienced the lowest level predicted for any of the treatment options is approximately 78%. Similarly, chlorophyll\_a concentrations are markedly reduced from levels as high as 16mg/m<sup>3</sup> to levels predicted to range between 2-4mg/m<sup>3</sup>.

In order to compare the model predictions against the EPA data it was necessary to calculate the average concentration of each of the parameters throughout the Lee Estuary / Lough Mahon waterbody. The model calculated the average concentration of each parameter in the following manner: for each cell in the waterbody the solute concentration was multiplied by the cell volume, this was then summed over the entire water body and divided by the sum of the volume of each cell in the water body. Figure 6 and figure 7 present the time series analysis of the average concentrations of DOX and CHL, respectively, within the Lee Estuary / Lough Mahon water body. Due to the relatively large surface area of Lough Mahon for reaeration, it is reasonable that figure 6 shows similar results of DOX for all simulations.

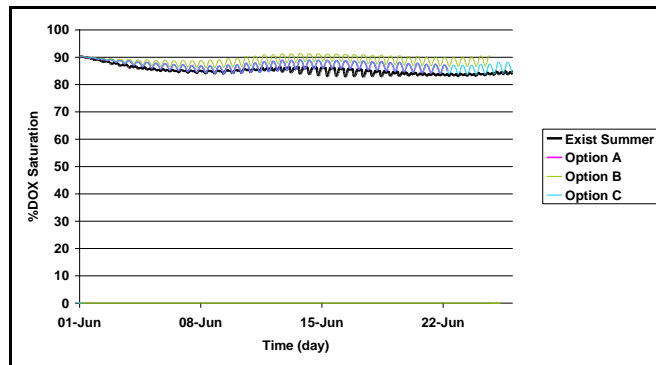


Figure 6: Lee Estuary / Lough Mahon average %DOX saturation level (Options A, B & C coincident).

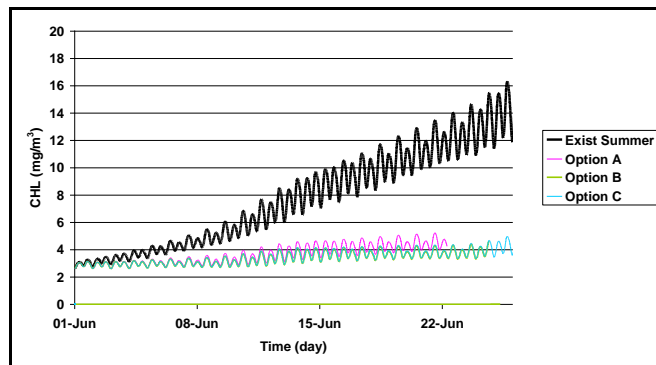


Figure 7: Lee Estuary / Lough Mahon average CHL concentrations (Options B & C coincident).

The arithmetic mean of the spatially averaged values was then calculated over two spring-neap cycles to obtain temporally and spatially averaged concentrations for each water quality parameter. These values were compared against the average of the values from the field data recorded over the summer months by the EPA from 1995 to 1999 and are shown in table 1.

Table 1: Comparison of average solute concentrations

Dataset	DOX (%sat)	CHL (mg/m <sup>3</sup> )
EPA	80.6	12.9
Existing	84.3	12.8
Option A - Proposed	87.3	4.1
Option B – Reduced N&P	89.8	3.6
Option C – Reduced P	87.3	3.6

It can be seen from the table that the arithmetic mean of the average values computed for the study area for the existing scenario show relatively good agreement with the average value obtained from the EPA data. Also, as shown at Location C in figure 4, the model can predict the low values of DOX saturation as recorded by the EPA. At Location C the model predicts DOX saturation levels as low as 5% saturation on 29th June with an average DOX saturation over the simulation of approximately 40%. The EPA sampled data at Location CO009 gives values as low as 11% DOX saturation and a mean value over June / July of 58% DOX saturation [7]. Both model predictions and EPA data of %DOX saturation at Location C show significantly lower values than the water body average values, as presented in table 1. This illustrates that the model is capable of reproducing trends in spatial gradients reasonably well.

Table 1 shows that the mean %DOX values for the three proposed scenarios are all higher than the existing condition, although there is very little difference between the three options. There is a marked improvement in the mean value of chlorophyll for all three scenarios; values are generally about 30% of the existing values, however, there is little variation between the three options.

#### 4.2 Trophic Assessment

As stated previously, the Irish Environmental Protection Agency consider that a section of tidal water is eutrophic if *all* of the criteria in relation to dissolved oxygen, chlorophyll\_a, dissolved inorganic nitrogen and orthophosphate have been exceeded. Therefore, if only three or less of the critical levels of any of the four parameters have been exceeded, the waterbody is not deemed eutrophic.

The criteria laid down for DOX and CHL pertain to summer conditions and are salinity dependant. Based on model predictions tidally averaged salinity during summer in the Lee Estuary and Lough Mahon was calculated at approximately 22psu. Relevant eutrophic criteria for waters of 22psu are presented in table 2.

Table 2: Comparison of model predictions and eutrophic criteria for dissolved oxygen (DOX) and chlorophyll\_a (CHL)

	DOX (%sat)	CHL (mg/m3)
Eutrophic criteria	73 (5 percentile)	13.6 (median)
Option A	87.3 (mean)	4.1 (mean)
Option B	89.8 (mean)	3.6 (mean)
Option C	87.3 (mean)	3.6 (mean)

Table 2 also compares mean values of water body averages of DOX and CHL for the Lee Estuary and Lough Mahon during typical summer conditions for each of the three treatment options. From the table it can be seen that model predictions of DOX (%sat) are considerably above desaturation values and model predictions of CHL are considerably below the eutrophic criterion.

From figure 4 it is seen that the lowest predicted DOX (%sat) value at location C, in the upper reaches of the Lee Estuary, is approximately 78. From inspection of figure 6 it is also observed that the lowest predicted value of average DOX (%sat) for any of the proposed Options is approximately 83. These values are well above the eutrophic criterion of 73.

From figure 7 it is seen that predicted levels of chlorophyll range between approximately 3–5mg/l; again these values are well below the maximum eutrophic criterion.

Therefore, the results indicate that the introduction of the new treatment facility and outfall at Carrigrennan will result in a marked improvement in the water quality of the Lee Estuary / Lough Mahon waterbody, so much so, that the waterbody would no longer be classified as eutrophic under the EPA Trophic Assessment criteria.

## 5 Conclusions

The primary objectives of this study were to assess the trophic status of the Lee Estuary and Lough Mahon water body for the following conditions:

- the existing prevailing discharges
- combining several discharges from a secondary treatment plant at Carrigrennan
- nitrogen and phosphorus reduction at Carrigrennan
- phosphorus reduction at Carrigrennan

The trophic status of the water body was assessed by analysing levels of dissolved oxygen saturation, chlorophyll\_a, dissolved inorganic nitrogen and orthophosphate. For the purpose of this paper, only dissolved oxygen saturation and chlorophyll\_a were discussed. The assessment was carried out in relation to the trophic assessment criteria laid out by the Irish Environmental Protection Agency.

Based on the model output, it may be concluded that the model was capable of accurately predicting the water quality within Cork Harbour, even where

localised spatial trends occurred. Dissolved oxygen saturation levels were found to be greatly improved for all treatment options, particularly in the Lee Estuary. Model predictions for the existing summer conditions show low values in the order of 10%, during all other simulations the values rarely fall below 80%. Chlorophyll\_a values were also reduced for all treatment options relative to the existing situation and the predicted Lee Estuary / Lough Mahon water body average values are lower than existing Lee Estuary / Lough Mahon water body average values.

From the model results it may be concluded that by implementing any of the proposed treatment Options A, B or C the trophic status of the Lee Estuary and Lough Mahon would be significantly improved and that the water body would no longer be classified as eutrophic.

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